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Design and implementation of MOEMS based ground to satellite free space optical link under turbulence condition

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Abstract

Non-mechanical beam steering techniques are commonly used in free space laser communication systems to avoid the use of massive opto-mechanical components. In this paper, we demonstrate an array-of-arrays of micro-opto-electro-mechanical system (MOEMS) based mirrors as a replacement for a large aperture reflective single-element mirror for ground to satellite optical links along with its associated electronic drive circuitry and FPGA based interface. The performance of the free space optical (FSO) communication link in terms of beam variance under atmospheric turbulence conditions is discussed.

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Keywords: Micro-opto-electro-mechanical systems; free space optics; acquisition; tracking; pointing; beam steering; turbulence; beam wander;

1. Introduction

Spatial acquisition, tracking and pointing (ATP) functions are critical to ground to satellite free space optical links. On-board ATP system acquires and tracks the signal from the earth station and accordingly adjusts the spacecraft orientation. Once the beacon signal is acquired successfully, the ATP system makes a transition to the

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tracking and pointing mode. Beam pointing is accomplished with the help of steering mirrors in the transmit beam path. For precise beam pointing, the beam needs to be steered in position and angle. For this purpose, it is necessary to implement very compact, lightweight and low power beam steering technologies. The most commonly used beam steerer is the piezoelectricity driven electromechanical device[1]. However, this device occupies a lot of space and has large processing time. Therefore the objective is to replace this bulky mirror beam steering system by lightweight micro-opto-electro-mechanical system (MOEMS) mirror based beam steering system. MOEMS systems are used to control optical signals on a very small size scale using integrated mechanical, optical and electrical systems. This technology allows fast tracking capabilities and accurate pointing between two transceivers.

In the subsequent sections, we discuss the design and working of a ground station based controller to simulate a communication system using MOEMS mirrors to point laser from ground station towards a satellite. Free space optical (FSO) communication link has atmosphere in the propagation path up to 20 km. For the study of atmospheric turbulence effect on FSO link performance, the requirement is to generate a turbulent atmospheric condition in a laboratory experiment. This is accomplished by using an optical turbulence generator (OTG) chamber that recreates temperature induced atmospheric turbulence condition[2]. The performance of the link is then tested at some practical turbulence levels.

2. System design and methodology

Fig. 1 outlines the major blocks of the system under consideration. The ground station consists of MOEMS mirror array, electronic control circuitry, positioning system and illuminating optics. Laser beam is collimated and reflected towards the satellite using the MOEMS mirrors. An on-board quadrant detector calculates the displacement of the laser beam from its center position and sends the error signal back to the ground station. Based on this error signal, the electronic circuitry moves the MOEMS mirror in order to correct the laser beam displacement. In the following sub-sections a detailed description of different parts of the system is given.

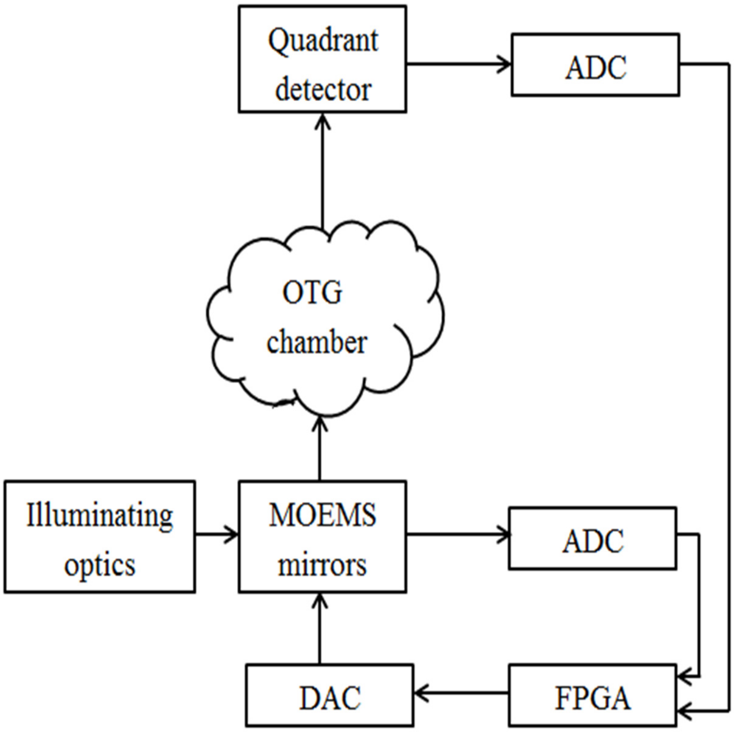

Fig. 1. System model of MOEMS mirror based FSO system.

2.1. MOEMS mirrors

MOEMS mirrors (shown in Fig. 2) use electromagnetic actuators for steering the mirror surface. Two analog voltages are required for controlling the X and Y axes to steer the mirror. It has a mechanical angular freedom of ±5º in each axis.

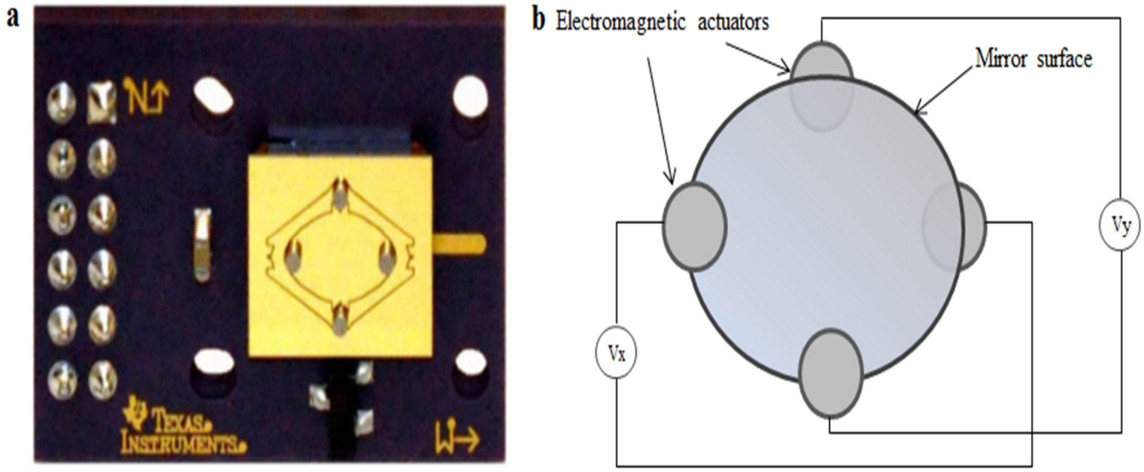

Fig. 2. (a) MOEMS mirror; (b) A simplified diagram of MOEMS mirrors.

2.2. Motorized positioning system

The mirror array is fitted on a jig which is mounted on a motorized platform called the goniometer using an interface plate. This motorized system can traverse up to ± 15º over a circular arc. Thus the goniometer, controlled by a single board controller (SBC), can provide a larger angular movement. Fig. 3 shows the MOEMS holding structure and the goniometer. The mirror holding structure is designed using CAD designing software ProEngineer[3].

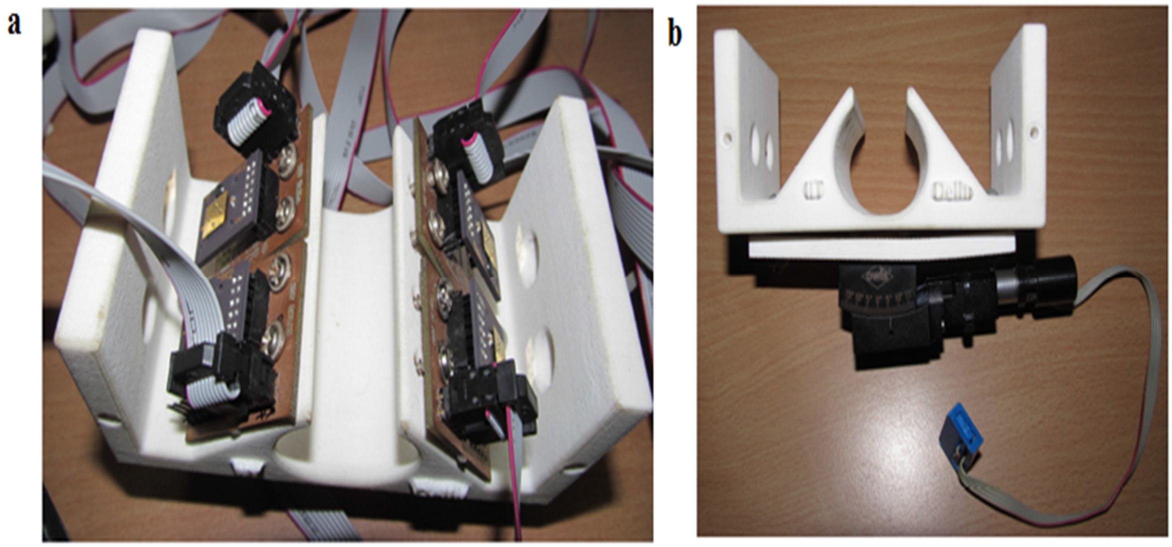

Fig. 3. MOEMS holding structure (a) With MOEMS; (b) On a goniometer using an interface plate.

2.3. Electronic control system

Control system is designed using Xilinx Virtex 2 Pro FPGA (field programmable gate array) board. FPGA with its user programmable gate array offers easy design, simple configuration, flexibleness and reusability. Since FPGAs are concurrent (i.e., tasks are performed simultaneously instead of sequentially), they are best suited for real time applications. The controller board has a hard wired embedded PowerPC 405 RISC processor block on which a RTOS is implemented to provide a multi-tasking environment. Xilkernal is native RTOS for embedded processors from Xilinx[4]. It provides a larger scalable functionality, responsiveness and robustness. Fig. 4 shows the architecture of the FPGA controller board.

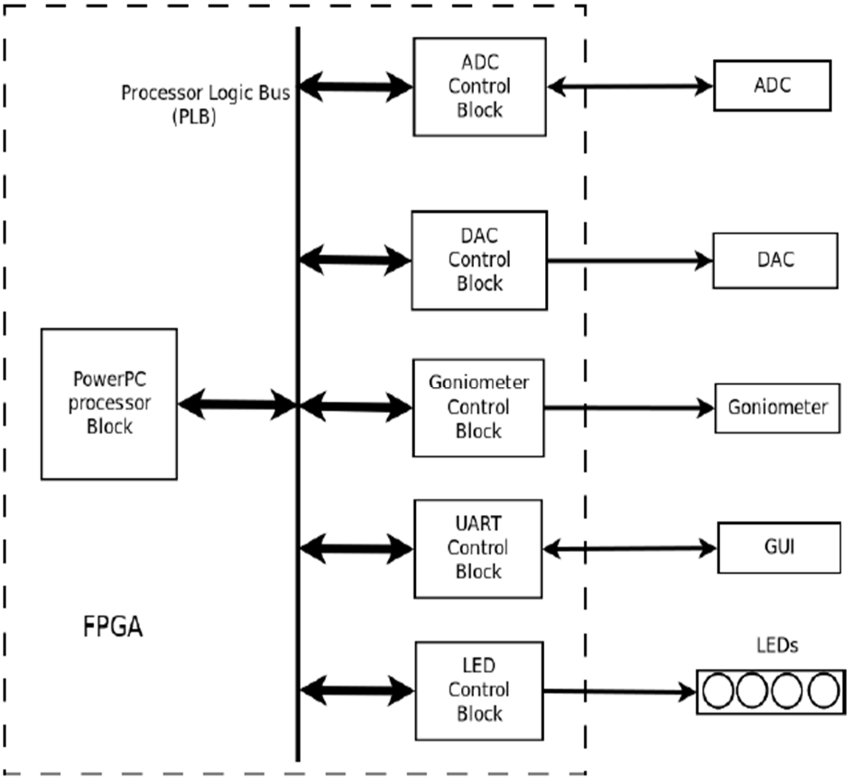

Fig. 4. Architecture of the FPGA controller board.

The function of the analog to digital converter is to read the current position of MOEMS mirrors and the error signal from the quadrant detector. Digital to analog converter supplies controlled analog voltages to MOEMS mirrors. UART controller sends and receives pre-defined data packets. Control signals for different hardware components are generated by making use of general purpose IP cores. The cores pins are connected to outside world through general purpose input output pins and to processor via on chip peripheral bus.

2.4. Positioning sensors

Positioning sensors help to generate the error signal due to displacement of the laser beam. As a starting alternative, either multi-element detector or position sensing detector (PSD) can be used. However, the former one has higher positional sensitivity, lower cost and greater operational simplicity as compared to the latter one. Although PSD has a greater range, the objective here is to align the beam rather than measuring a continuous displacement. So, we choose a quadrant detector which measures the displacement of the laser from its center and sends the error value to the ground station for the realignment of the beam. Positioning signal provides error signal in form of an analog signal which is digitized using ADC board and transmitted on E1 telemetry link.

3. Results and discussions

The work is divided into two phases: in the first phase beam wander is analyzed in terms of beam variance (in units of meter square) for different temperatures. The square of the deviation of the point of maximum intensity of the beam is defined as the beam variance[5]. The experimental set-up of beam wander measurement is shown in Fig. 5.

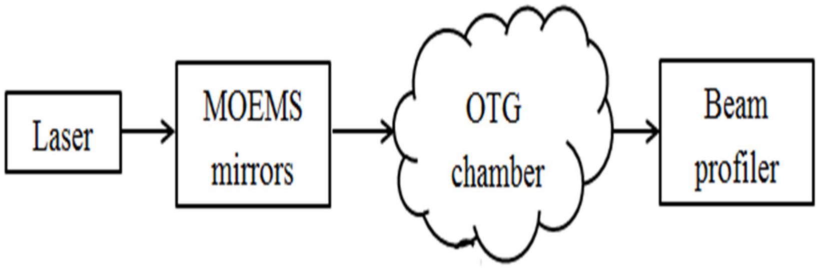

Fig. 5. Experimental set-up for the measurement of beam variance.

Within the OTG chamber the air at room temperature is mixed with hot air, heated by using an electric heater, to generator turbulence. The beam emerging out of the chamber after being affected by the turbulence is captured by a beam profiler. The BeamGage software measures the beam variance from the captured profile[2]. Fig. 6 shows the beam variance for different temperatures. With increase in temperature beam variance increases implying degradation in the FSO link performance.

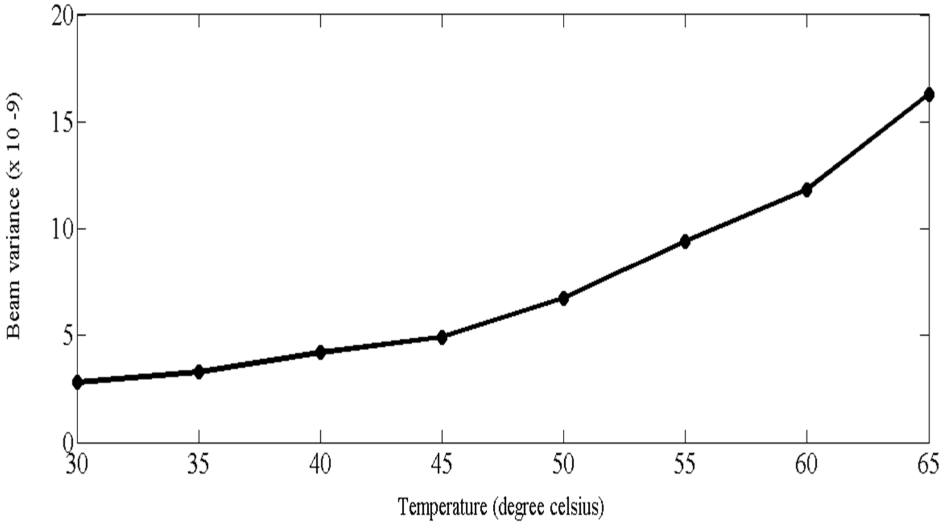

Fig. 6. Beam variance vs. temperature.

In the second phase, the electronic control system based on FPGA is implemented along with software interface for manual control of MOEMS mirrors. The performances of the real time control application and the prototype of control electronics are analyzed.

For testing and performance analysis of prototype of the control electronics we input different patterns of disturbance like AC signals of different frequencies. The corresponding outputs are observed on the oscilloscope and compared with the input signals[5]. The basic block diagram for feasibility study of electronic control system is shown in Fig. 7.

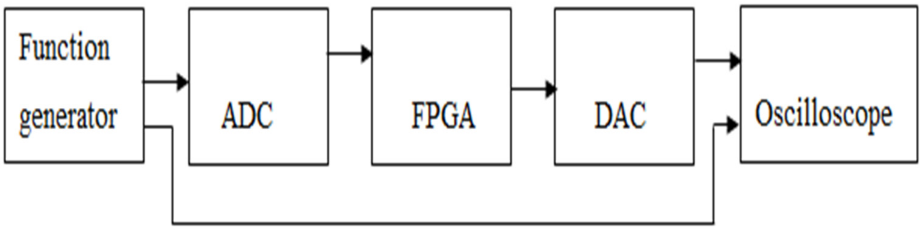

Fig. 7. Set-up for feasibility study of electronic control system.

The various signals are fed at ADC input and the outputs are measured at DAC output. Figs. 8(a) and (b) show the response for sinusoidal inputs.

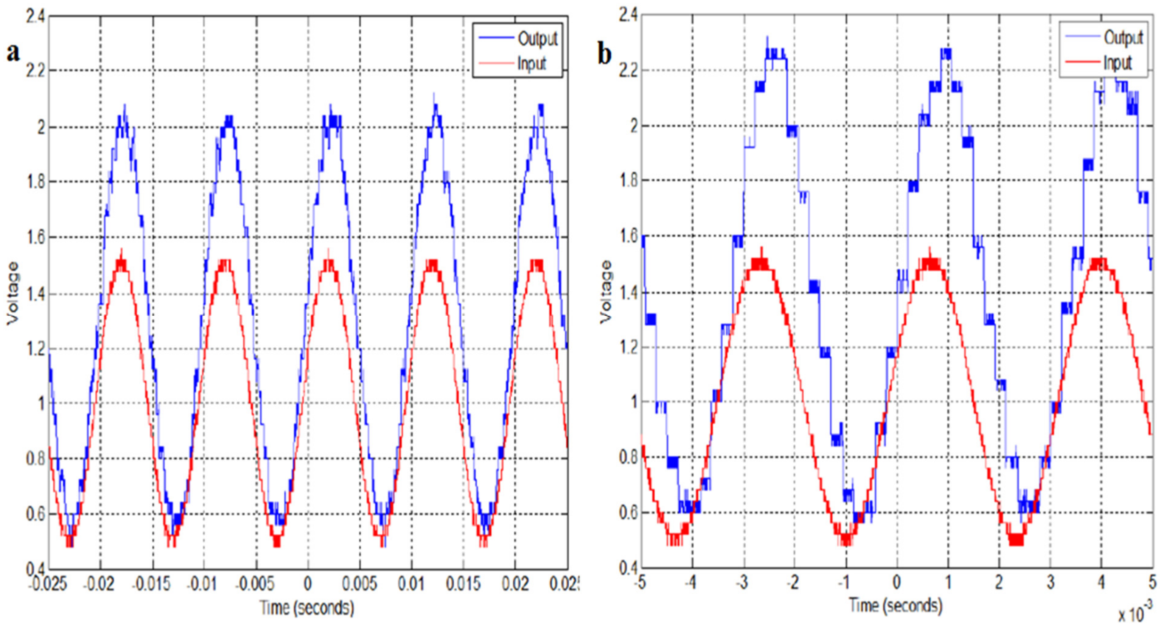

Fig. 8. Response for (a) 100 Hz sinusoidal; (b) 300 Hz sinusoidal signals.

At 100 Hz sinusoidal input, the output of the prototype begins to show phase difference. This phase difference increases as frequency increases. Thus the prototype developed shows good frequency response at frequencies lower than 100 Hz.

The performance of the real time control application developed for steering the MOEMS mirror is evaluated in terms of the following parameters: MOEMS settling time, system initialization time and task delay for ADC, DAC and goniometer. Table 1 summarizes the performance parameters. When MOEMS mirror is moved with full fluctuation of ±5º, a large settling time is observed. However, when the MOEMS mirror is moved in small steps by software damping of the DAC output, a smaller settling time is observed since change in small steps does not cause excessive movement of the mirror. RTOS takes a constant time for initialisation. Also some jitter is observed in execution of ADC and DAC as these tasks have low priority in comparison to the communication task of higher priority.

Table 1. Performance parameters of real time control application

Parameters	Min	Average	Max
MOEMS Settling Time (Full Swing)			
Without Damping (X)	1.8 s	2.1 s	2.6 s
With Damping (X)	310 ms	560 ms	810 ms
Without Damping (Y)	1.2 s	1.6 s	1.8 s
With Damping (Y)	270 ms	310 ms	430ms
Task Delay			
ADC (Single Channel)	330 ns	331 ns	331 ns
DAC Single Channel (Minimum Step Change)	120 ns	130 ns	160 ns
DAC Single Channel (Maximum Step Change)	460 ns	485 ns	496 ns
Goniometer (Swing for 1º)	3.1 s	3.1 s	3.1 s
System Initialization Time	510 ns	510 ns	510 ns

4. Conclusions

In summary, we have implemented an array of arrays of MOEMS mirror based free space optical link. The motivation was to replace the large and bulky beam steering mirror with small sized MOEM system. Beam wander characteristics of this link shows increase in beam variance with temperature implying the degradation in the link performance under turbulence conditions. We have designed and developed the control circuitry for optical steering of the beam. The electronic prototype was developed with good low frequency response. MOEMS mirror showed a higher settling time for large swing. Settling time was minimized by software damping but at the cost of increased driver execution time.

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